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Investigation of hot hole distribution and real space transfer by interband absorption in p-type InGaAs/GaAs MQW heterostructures

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Abstract. Lateral electric field (up to 2 kV/cm) effects on transmittance in selectively doped p-type MQW In_xGa_{1-x}As/GaAs heterostructures with delta-doped barriers have been studied. The peculiarities of the transmittance spectra associated with hole transitions from the acceptors to the quantum wells and with the hole escape from the quantum wells into the GaAs barriers have been observed. The hole effective temperature in the quantum wells and the population of impurity states in high electric fields were obtained.

In recent papers [1-3] the far IR emission and absorption as well as photoluminescence (PL) from 2D hot holes in MQW In_xGa_{1-x}As/GaAs heterostructures at lateral transport has been investigated experimentally. The remarkable high nonequilibrium phenomena in the high electric fields were revealed under real space transfer (RST) [4] and the new mechanism of the intraband population inversion and far IR lasing was put forward [5,6]. The paper presents the first study of lateral electric field effects on the optical transmittance of p-type InGaAs/GaAs heterostructures under RST. Investigations of optical transmittance allowed us to study directly the energy hole distribution in the quantum wells and hole population on the acceptors under heating by high lateral electric field.

In_xGa_{1-x}As/GaAs heterostructures ($0.07 < x < 0.2$, $d_{\text{InGaAs}} = 4.5$ to 10 nm, $d_{\text{GaAs}} = 60$ nm, $n_{\text{QW}} = 20$) were grown by MOCVD technique at atmospheric pressure on semi-insulating GaAs (001) substrates. Two delta-layers of Zn were introduced at 5 nm from both sides of each In_xGa_{1-x}As quantum well in GaAs barrier layers. Typical values of 2D hole concentration were of $p_s = (0.6 \text{ to } 1.7) \times 10^{11} \text{ cm}^{-2}$. The lateral pulsed electric field (E) up to 2 kV/cm 5 to 10 μs in duration was applied to the structure via strip electric contacts deposited on the sample surface at the distance 3 to 4 mm. In addition to the transmittance the PL for the samples at $E = 0$ was also investigated. PL was excited by cw Ar⁺ laser, dispersed by monochromator and detected by cooled photomultiplier. In transmittance experiments the light from halogen lamp was dispersed by monochromator and guided to the sample by optical fibre and detected by Ge-diode placed behind the sample. The measurements were carried out at 4.2 K. In all experiments boxcar integrator was used for data acquisition. In transmittance experiments the measured signal was proportional to the difference between the intensities of light passed through the sample without and under applied electric field.

In Fig. 1 the schematic energy band diagrams and the main optical transitions for two types of investigated heterostructures (a and b) are shown. In the heterostructures with deep quantum wells ($x \approx 0.18$ to 0.2 , $d_{\text{InGaAs}} \approx 8$ to 10 nm) the energy of the

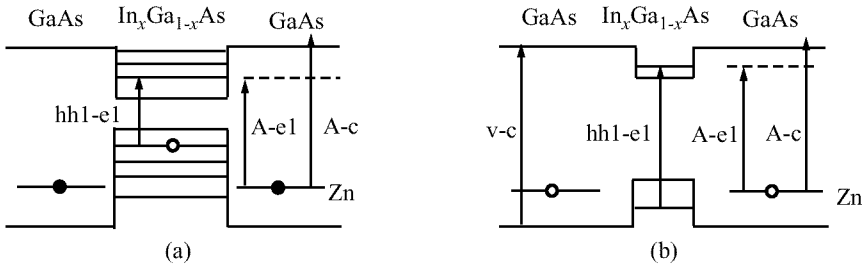


Fig 1. Energy zone diagrams for heterostructures with deep (a) and shallow (b) quantum wells. Possible optical transitions are shown by the arrows: hh1-e1—first heavy hole level—first electron level, A-c—acceptor—conduction band of GaAs, A-e1—acceptor—first electron level, v-c—valence band—conduction band of GaAs.

first heavy hole level (hh1) in the quantum wells with respect to the valence band edge in GaAs exceeds that of the ground state of the ionization energy of the acceptors (31 meV for Zn) and at zero electric field the acceptors are completely ionized and all holes turn to be in the quantum wells. In the heterostructures with narrow and shallow quantum wells ($x \approx 0.07$ to 0.1 , $d_{\text{InGaAs}} \approx 4.5$ to 5.5 nm) the energy of the first heavy hole level in the quantum well is less than the acceptor in the barrier and at zero electric field the holes are frozen at the impurities. Current-voltage characteristics in these heterostructures exhibit sharp current increase at electric field of the order of 0.3 to 0.6 kV/cm due to impact ionization of the acceptors [1].

In heterostructures with deep quantum wells at zero electric field the hole concentration in the quantum wells is high and therefore the edge of the fundamental absorption is shifted to the shortwavelength region due to Burstein-Moss effect. Hole heating results in the change of the hole distribution and hence in the tailing of the fundamental absorption edge. This leads to both the increase of the sample transmittance at the energies ($\hbar\omega$) higher than Fermi energy and the decrease of the energies lower than Fermi energy (Fig. 2a). PL spectrum at $E = 0$ is also given in Fig. 2 for comparison. The widths of low energy “negative” peaks in the transmittance modulation spectra as well as of PL one are determined by the fluctuation of the quantum wells parameters and existing of the state density tails in band gap. The widths of high energy peaks in the transmittance modulation spectra specify the effective temperature of hot holes in the quantum wells (T_w) that reaches approximately 300 K in intermediate electric fields and does not change at the further increase of the electric field due to high optical phonon scattering. It is clearly seen from Fig. 2a that at $E > 1.2$ kV/cm the saturation of low energy “negative” peak takes place. This saturation seems to result from the depopulation of hole states in the quantum wells i.e. the hole occupation numbers tend to zero. In Fig. 2a one can see that in the moderate electric fields 0.3 to 0.6 kV/cm the integral intensity of the “negative” peak is approximately the same as the “positive” one. This relation corresponds to the conservation of the hole number in the quantum wells. However at higher electric fields up to 1.2 kV/cm the intensity of “negative” peak increases while that of the “positive” one saturates that evidently indicates the escape of hot holes to barrier layers, i.e. RST.

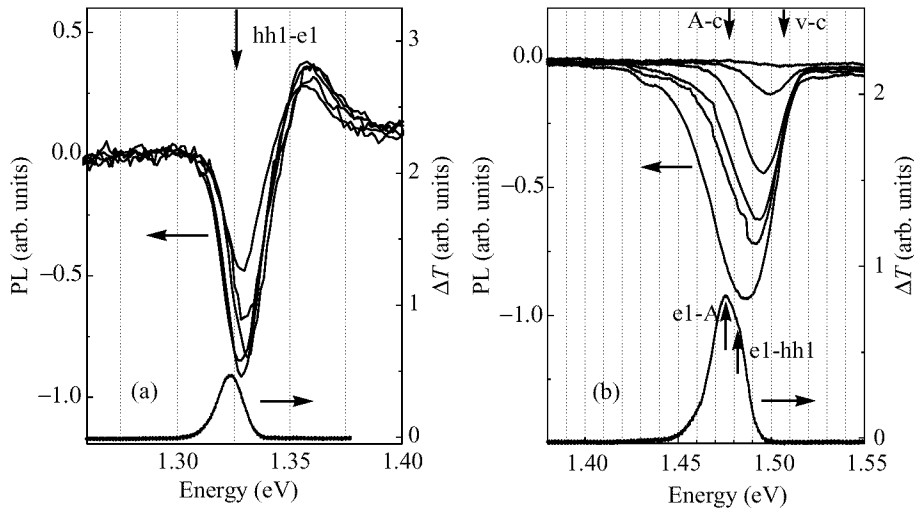


Fig 2. PL (at $E = 0$) and transmittance modulation spectra for 10 nm $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}/\text{GaAs}$ (a) and for 5.5 nm $\text{In}_{0.08}\text{Ga}_{0.92}\text{As}/\text{GaAs}$ (b) quantum wells for lateral electric field (kV/cm): 1—0.38, 2—0.63, 3—0.95, 4—1.26, 5—1.58, 6—1.9.

In heterostructures with shallow quantum wells the transmittance modulation was not observed up to electric fields corresponding to the acceptor breakdown ($E \approx 0.3$ kV/cm). The breakdown results in the hole transfer from acceptors to the quantum wells. Ionization of acceptors leads to the increase of impurity-conduction band absorption and hence to the transmittance modulation in the frequency region in between A-c and v-c transitions (Fig. 2b). The amplitude of the negative modulation rises with the electric field thus testifying the increase of the number of the ionized acceptors. In some samples the saturation of transmittance modulation was observed that seems to result from the ionization of the most part of the impurities. In contrast to the deep quantum wells in the shallow ones no positive transmittance modulation connected with the carrier redistribution in the quantum wells was observed (cf. Fig. 2a and Fig. 2b). This result from the fact that the dominant mechanism of the modulation in the shallow quantum wells is the ionization of the acceptors. The other optical transitions seems to be responsible only for the changes in the form of spectral line and in particular in the observed low-energy shift of the modulation maximum (Fig. 2b).

Thus the transmittance measurements in high lateral electric fields are shown to be a sensitive tool to probe hot carrier distributions in deep quantum wells. The obtained high value of the hole effective temperature $T_w = 300$ K is the necessary condition for the realisation of the population inversion between barrier and quantum well states [6]. The results obtained from the transmittance modulation in the shallow quantum wells give the additional information on the population of impurity states in high electric fields that is significant for the “design” of the RST laser structure.

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